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Published in:
Monthly Notices of the Royal Astronomical Society

DOI:
[10.1046/j.1365-8711.2001.04107.x](https://doi.org/10.1046/j.1365-8711.2001.04107.x)

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Document Version
Publisher's PDF, also known as Version of record

Publication date:
2001

[Link to publication in University of Groningen/UMCG research database](#)

Citation for published version (APA):

Nusser, A., da Costa, L. N., Branchini, E., Bernardi, M., Alonso, M. V., Wegner, G., Willmer, C. N. A., & Pellegrini, P. S. (2001). Comparison of the ENEAR peculiar velocities with the PSCz gravity field. *Monthly Notices of the Royal Astronomical Society*, 320(3), L21-L24. <https://doi.org/10.1046/j.1365-8711.2001.04107.x>

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Comparison of the ENEAR peculiar velocities with the PSCz gravity field

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Accepted 2000 October 11. Received 2000 September 15; in original form 2000 June 9

ABSTRACT

We present a comparison between the peculiar velocity field measured from the ENEAR all-sky D_n – σ catalogue and that derived from the galaxy distribution of the *IRAS* Point Source Catalog Redshift Survey (PSCz). The analysis is based on a modal expansion of these data in redshift space by means of spherical harmonics and Bessel functions. The effective smoothing scale of the expansion is almost linear with redshift reaching 1500 km s^{-1} at 3000 km s^{-1} . The general flow patterns in the filtered ENEAR and PSCz velocity fields agree well within 6000 km s^{-1} , assuming a linear biasing relation between the mass and the PSCz galaxies. The comparison allows us to determine the parameter $\beta = \Omega^{0.6}/b$, where Ω is the cosmological density parameter and b is the linear biasing factor. A likelihood analysis of the ENEAR and PSCz modes yields $\beta = 0.5 \pm 0.1$, in good agreement with values obtained from Tully–Fisher surveys.

Key words: cosmology: observations – dark matter – large-scale structure of Universe.

1 INTRODUCTION

In the standard picture for the formation of cosmic structures via gravitational instability, the peculiar velocity of a galaxy is generated by fluctuations in the mass distribution. For galaxies outside virialized systems, linear perturbation theory predicts

$$\mathbf{v}(\mathbf{r}) \approx \frac{\Omega^{0.6} H_0}{4\pi} \int d^3 r' \delta_m \frac{(\mathbf{r}' - \mathbf{r})}{|\mathbf{r}' - \mathbf{r}|^3}, \quad (1)$$

where Ω is the mass density parameter, H_0 is the Hubble constant and δ_m is the mass density fluctuation field. If the relationship between the galaxy distribution, δ_g , and δ_m is approximately linear, $\delta_g = b\delta_m$, then the parameter $\beta = \Omega^{0.6}/b$ can be derived from the comparison between the observed peculiar velocity field and that predicted from the galaxy distribution. A particularly useful method for performing a velocity–velocity comparison is the modal expansion method developed by Nusser & Davis (1995, hereafter ND95). This method expands the velocity fields by means of smooth functions defined in redshift space, thus alleviating the Malmquist biases inherent in real-space analysis. Furthermore, the modal expansion filters the observed and predicted velocities in the same way, so that the smoothed fields

can be compared directly. Because the number of modes is substantially smaller than the number of data points, the method also provides the means of estimating β from a likelihood analysis carried out on a mode-by-mode basis, instead of galaxy-by-galaxy. The similar smoothing and the mode-by-mode comparison substantially simplify the error analysis. The modal expansion method has previously been used in comparisons between the 1.2-Jy *IRAS* predicted velocities and observed velocities inferred from Tully–Fisher (TF) measurements (Davis, Nusser & Willick 1996, hereafter DNW; da Costa et al. 1998). In this paper, we perform a similar analysis using the recently completed redshift–distance survey of early-type galaxies (hereafter ENEAR: da Costa et al. 2000) and the *IRAS* Point Source Catalog Redshift Survey (PSCz) (Saunders et al. 2000). Because of differences in the nature of the data sets considered, some slight changes in the method are required and are described below. Our goal is to investigate how well the velocity field mapped by early-type galaxies matches the velocity field inferred from the PSCz, and to obtain the parameter β yielding the best match.

In Section 2, we briefly describe the ENEAR redshift–distance catalogue. In Sections 3 and 4, we describe the modal expansion method as used here, present maps of the ENEAR and PSCz radial peculiar velocity field and perform a likelihood analysis to derive β . A brief summary of our conclusions is presented in Section 5.

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2 DATA

We use a subsample extracted from the all-sky ENEAR redshift–distance survey (da Costa et al. 2000) comprising 578 objects within $cz \leq 6000 \text{ km s}^{-1}$ – 355 field galaxies and 223 groups/clusters. Galaxies have been objectively assigned to groups and clusters using redshifts taken from complete redshift surveys sampling the same volume. Individual galaxy distances were estimated from an inverse D_n – σ template relation derived by combining cluster data (e.g. Bernardi et al., in preparation). The cluster sample consists of 569 galaxies in 28 clusters. Over 80 per cent of the galaxies in the magnitude-limited sample and roughly 60 per cent of the cluster galaxies have new spectroscopic and photometric data obtained by the ENEAR survey. Multiple observations using different telescope/instrument configurations ensure the homogeneity of the data. Furthermore, the sample completeness is uniform across the sky.

3 THE MODAL EXPANSION

An unbiased estimate of $\beta = \Omega^{0.6}/b$ can be obtained from the comparison between smooth velocity fields with similar spatial resolution, derived from the ENEAR and PSCz data. To generate smooth fields we expand the peculiar velocities of both data sets in terms of smooth base functions. The expansion carried out here shares the general properties of that used by ND95, but differs in details. In their application to TF catalogues, ND95 defined $P_i \equiv 5 - \log(1 - u_i/s_i)$, where $s_i = cz_i$ is the galaxy redshift in km s^{-1} and u_i its radial peculiar velocity. The function P was then expressed by an expansion involving smooth functions. The final estimate of the smoothed velocity field was that obtained by minimizing the scatter of the rotational speeds given the magnitudes in the inverse TF relation. The scatter was also simultaneously minimized with respect to the parameter of the TF relation. This led to an unbiased calibration of the inverse TF relation because the sample was mainly magnitude-selected. The galaxy angular size and velocity dispersion in the D_n – σ relation do not uniquely fix the magnitude according to which the ENEAR sample is selected. So simultaneous minimization might lead to a biased estimate of the parameters of the D_n – σ relation. Although the bias is mild, we use the calibration of the *inverse* D_n – σ given by Bernardi et al. (in preparation) by a regression of σ on D_n in clusters. We also express the peculiar velocity, u , rather than the function P in terms of smooth functions. Another difference is that ND95 used TF catalogues with all galaxies having the same relative distance error, which allowed an additional simplification in the application of the modal expansion method, namely, the expansion in terms of orthogonal smooth functions. This made the TF velocity error covariance matrices diagonal. In the ENEAR sample, the relative distance error is not the same for all objects (galaxies and groups/clusters), so using orthogonal functions does not offer any further simplification since the ENEAR error matrix remains non-diagonal. The lack of orthogonality slightly complicates the error analysis but does not affect the efficiency of the expansion. Choosing the spherical harmonics and Bessel functions to be our base smooth functions, we write the radial peculiar velocity model as

$$\tilde{u}(s, \theta, \phi) = \sum_{l,m,n} \alpha_{nlm} [j'_l[k_n y(s)] - c_{l1}] Y_{lm}(\theta, \phi), \quad (2)$$

where the sum is over $m = -l$ to $+l$, $l = 0$ to l_{\max} and $n = 0$ to

n_{\max} . We formulate our model to describe the velocity field with respect to the motion of the Local Group. This has the advantage that any external dipole in the mass distribution does not affect the PSCz recovered velocities (see DNW). The constant c_{l1} is non-zero only for the dipole term ensuring that $u = 0$ at the origin. The function $y(s)$ in the argument of the Bessel functions makes their oscillations match the radial distribution of the ENEAR data. Here we take $y^2 = \ln[1 + (s/1000)^2]$, but other similar forms can be used as well. Since we work with velocities relative the Local Group frame, any external dipole mass distribution does not affect the reconstructed velocities in the interior region. As in DNW we add to the expansion a term describing an external quadrupole mass distribution beyond the redshift limit of the PSCz catalogue. However, it turns out that the inclusion of this term has a negligible effect on the expansion of the velocity fields in terms of the modal expansion. We remove that Hubble-like ($u \propto s$) flow from the ENEAR and PSCz velocities, so the expansion does not include a Hubble-like flow. The coefficients α_{nlm} are found by minimizing

$$\chi^2 = \sum \sigma_i^{-2} [\tilde{u}_i - u_i^o]^2, \quad (3)$$

where u_i^o are the raw observed velocities and σ_i is the error of the velocity estimate resulting from observational uncertainties and intrinsic scatter in D_n – σ . For field galaxies $\sigma_i = 0.23s_i$ (Bernardi 1999; Bernardi et al., in preparation) and for groups of galaxies it is reduced by $1/\sqrt{N_g}$, where N_g is the number of galaxies in the group.

4 SMOOTH VELOCITY MAPS AND THE DETERMINATION OF β

We apply the modal expansion method to smooth the raw measured velocities of the 578 ENEAR objects within a redshift of 6000 km s^{-1} (Bernardi et al., in preparation). We use 51 modes corresponding to $l_{\max} = 4$, $n_{\max} = 3$ in equation (2). The smoothing scale of these functions is linear with redshift and matches the low-resolution filter used in da Costa et al. (1998) (see their fig. 1). The smoothed velocities are then derived by minimizing equation (3) with respect to α_{lmn} assuming an error of $\sigma_i = 0.23s_i/\sqrt{N_g}$ in the raw velocities of the ENEAR objects. The reduced χ^2 per d.o.f of the fit is 1.017, a satisfactory value in this type of analysis (see DNW; da Costa et al. 1998).

Given an assumed value for β , we interpolate the PSCz predicted velocity field, computed by Branchini et al. (1999), to the positions of the ENEAR galaxies. Branchini et al. obtained the PSCz velocities from the PSCz galaxy distribution with a top hat window of width equal to half the mean particle separation at a given redshift. The PSCz fields are then expanded in the same orthogonal set of basis functions as employed for the ENEAR velocities. The PSCz and ENEAR velocities are guaranteed to have the same resolution because the original smoothing of the PSCz density field is small compared with the resolution of the modal expansion.

The smoothed ENEAR velocities are shown in Fig. 1, in redshift shells 2000 km s^{-1} thick. Comparison of this figure and fig. 3 of da Costa et al. (1998) shows that the general flow pattern is remarkably similar. In the case of ENEAR, in the innermost shell very few prominent structures are probed by bright ellipticals. However, in the next two shells a strong dipole pattern can be easily recognized, being of comparable amplitude to that observed with the SFI sample of spiral galaxies. This dipole

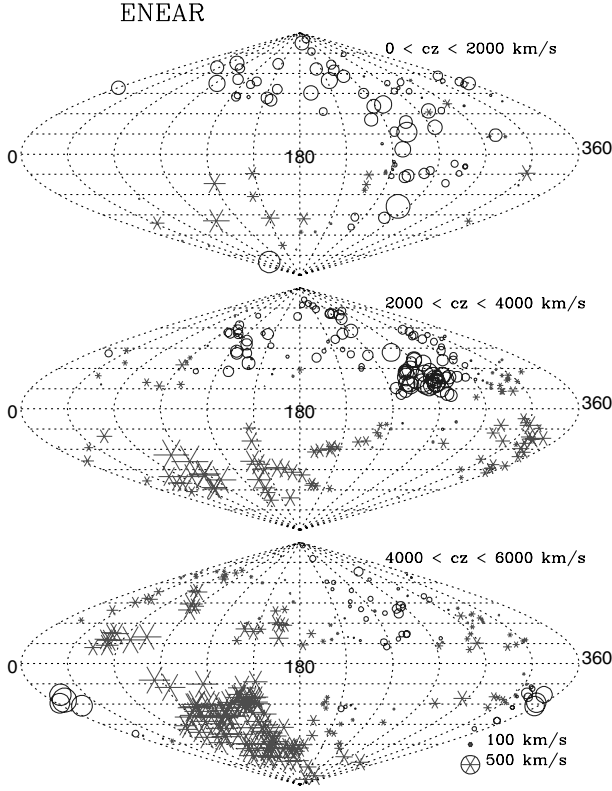


Figure 1. The sky projection in galactic coordinates as seen in the Local Group frame of the filtered ENEAR velocity field.

corresponds to the reflex motion of the Local Group, with infalling galaxies in the Hydra–Centaurus direction and an outflow towards the Perseus–Pisces complex. The quality of the match can be evaluated from Fig. 2 which shows the residual velocity field obtained by subtracting the smoothed PSCz field from that of the ENEAR, assuming $\beta = 0.5$. As can be seen the overall agreement is good, with only a few more distant galaxies giving large residuals. Note, however, that the mismatch in the outermost redshift shell, at $l \sim 0^\circ$, $-60^\circ \lesssim b \lesssim -15^\circ$, between ENEAR and PSCz is also seen in the comparison between the SFI and 1.2-Jy *IRAS* velocity fields. This may correspond to a real mismatch between measured and predicted velocities which deserves further investigation.

The filtered ENEAR and PSCz velocity fields are fully described by the modal expansion coefficients, α_{en} and α_{ps} , of the ENEAR and PSCz fields, respectively. Since the number of these coefficients is significantly smaller than the number of galaxies, it is more efficient to estimate β by comparing the modes rather than the individual galaxy velocities. As in da Costa et al. (1998), we define our best estimate for β as the value that corresponds to the minimum of the pseudo- χ^2

$$\tilde{\chi}^2(\beta) = \sum_{j,j'} [\alpha_{\text{en}}^j - \alpha_{\text{ps}}^j(\beta)] [\mathbf{T} + \mathbf{M}(\beta)]^{-1} [\alpha_{\text{en}}^{j'} - \alpha_{\text{ps}}^{j'}(\beta)], \quad (4)$$

where $\mathbf{T} \equiv \langle \delta\alpha_{\text{en}}^j \delta\alpha_{\text{en}}^{j'} \rangle$ and $\mathbf{M} \equiv \langle \delta\alpha_{\text{ps}}^j \delta\alpha_{\text{ps}}^{j'} \rangle$ are the error covariance matrices of the coefficients α_{en}^j and α_{ps}^j , respectively. For brevity of notation we have replaced the triplet n, l, m with one index j . The PSCz covariance matrix \mathbf{M} incorporates errors owing to (i) the uncertainty in the Local Group motion, which creates a dipole discrepancy between the ENEAR and the PSCz velocities, (ii) the discreteness in the distribution of galaxies which propagates into the velocity field, and (iii) small-scale, coherent

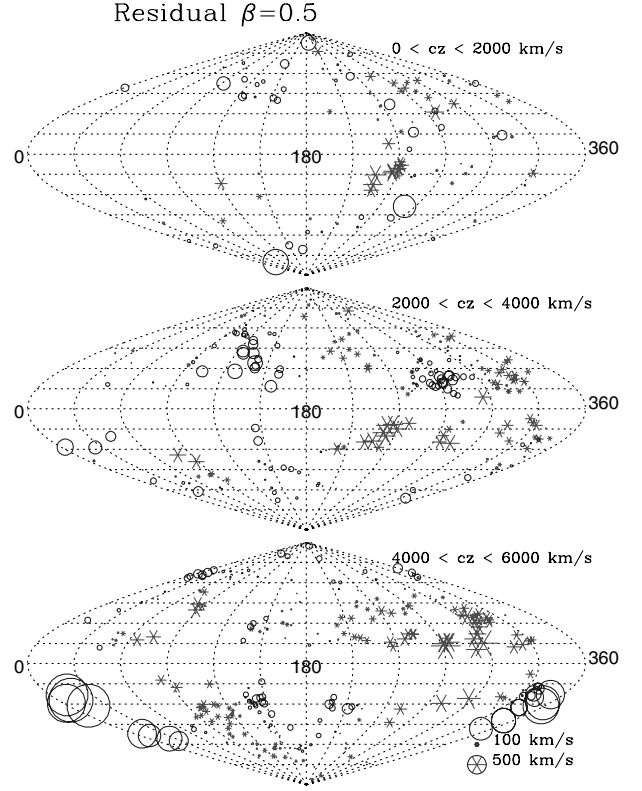


Figure 2. The residual velocity field (ENEAR minus PSCz) for $\beta = 0.5$.

(as in triple-valued zones) and incoherent (velocity dispersion), non-linear velocities that are not included in the PSCz recovered velocities. Details of how these error contributions are computed are in da Costa et al. (1998). Since the expansion functions are not orthogonal, the ENEAR covariance matrix \mathbf{T} has non-zero off-diagonal elements. This matrix is simply the inverse of $\partial^2 \chi^2 / \partial \alpha_{\text{en}}^j \partial \alpha_{\text{en}}^{j'}$, where the derivatives are computed at the minimum of χ^2 given by equation (3).

Given the covariance matrices, we compute the curve of the reduced $\tilde{\chi}^2(\beta)$ as a function of β , which is shown in the top panel of Fig. 3. The curve was computed with an error of 150 km s^{-1} in the estimation of the Local Group motion and 160 km s^{-1} for the amplitude of the non-linear error in the PSCz field (see da Costa et al. 1998). This amplitude of the non-linear error was chosen to make the $\tilde{\chi}^2$ per d.o.f equal to unity at the minimum. In their analysis of the SFI and 1.2-Jy *IRAS* data, da Costa et al. (1998) obtained a lower value of 90 km s^{-1} for the amplitude of this error. The difference can be attributed, as expected, to a better match between the SFI and *IRAS* velocities and the increased non-linearities in the PSCz velocity at the positions of the ENEAR galaxies which preferentially reside in high-density regions.

The minimum value of the $\tilde{\chi}^2$ is attained at $\beta = 0.5$, with the 1σ error being less than 0.1. We note that this result is not sensitive to the exact values adopted for the error estimates. Another statistic indicating the goodness of the match between the fields for various β is the correlation function of the residual $u_{\text{en}} - u_{\text{ps}}$ between the smoothed ENEAR and PSCz radial velocities. This is shown in the bottom panel of Fig. 3 for $\beta = 0.2, 0.5$ and 0.9 . The amplitude of the PSCz field is small for $\beta = 0.2$, so the correlation function for this β is close to the correlation function of u_{en} alone, while the opposite is true for $\beta = 0.9$. On the other

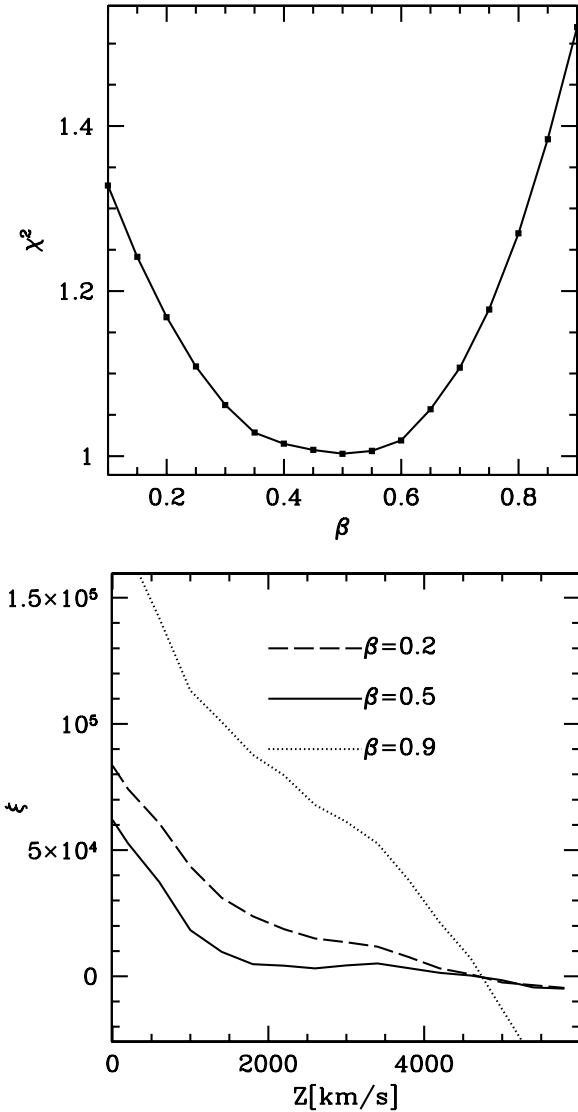


Figure 3. Top panel: the curve of reduced pseudo- χ^2 versus β computed using equation (5). The number of degrees of freedom is 557. Bottom panel: the correlation function of the velocity residual field for $\beta = 0.2$, 0.5 and 0.9.

hand, for $\beta = 0.5$ the correlation of the residual velocity field is significantly smaller, indicating a good match between the measured and predicted velocity fields.

5 SUMMARY AND DISCUSSION

Using the modal expansion method of ND95 and the recently completed ENEAR redshift–distance survey and the PSCz redshift survey, we have carried out a comparison between the observed peculiar velocity field and that predicted from the

distribution of PSCz galaxies. We find that the corresponding smoothed fields agree well and the best match is obtained with $\beta = 0.5 \pm 0.1$. This value is intermediate to those derived using the Mark III and SFI catalogues, both based primarily on spiral galaxies. It is also consistent with the results obtained by Borgani et al. (2000) using an independent method based on modelling the velocity correlation function. The value is also favoured from analysis of the PSCz catalogue (e.g. Tadros et al. 1999; Hamilton, Tegmark & Padmanabhan 2000; Valentine, Saunders & Taylor 2000). Note, however, that the discrepancy between the values determined from these methods and those obtained from power spectrum analysis (e.g. Zaroubi et al. 2000) and density–density comparisons (e.g. Sigad et al. 1998) still persists. The good agreement between SFI and 1.2-Jy *IRAS* and between ENEAR and PSCz implies that the SFI and ENEAR velocity fields are also in good agreement. This suggests that the velocity maps obtained from the new distance–redshift surveys are a fair representation of the underlying velocity field, as the general characteristics of the observed flow fields are independent of the type of galaxies and distance indicators used. The good agreement among the values of β obtained using the Mark III, SFI, ENEAR, 1.2-Jy and PSCz catalogues gives further support to low values of β and points toward low-density cosmologies.

ACKNOWLEDGMENTS

The authors thank M. Maia, C. Rit   and O. Chaves for their contribution over the years. We also thank the referee, Will Saunders, for many useful comments. The results of this paper are based on observations conducted at the European Southern Observatory (ESO) and the MDM Observatory. CNAW acknowledges support from NSF AST95-29028.

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